RESEARCH BRIEF

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Availability of biomass feedstocks in the European Union to meet the 2035 ReFuelEU Aviation SAF target

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INTRODUCTION

This briefing updates the 2021 analysis by the International Council on Clean Transportation (ICCT) of feedstock availability for sustainable aviation fuel (SAF) in the European Union (EU).[1] The final adoption of the ReFuelEU Aviation regulations in October 2023 offers a clear understanding of the types of feedstocks and fuels that will be eligible to meet interim SAF blending targets.

We assessed the availability of biomass materials in the EU that meet ReFuelEU's eligibility criteria and a subset of those materials that could be sustainably supplied to the aviation sector, which we define as "lowest risk" of all the eligible biofuels, to meet the 2035 SAF target. ReFuelEU restricts eligibility to biofuels that are not produced from "food and feed crops." Eligible fuels include biomass listed in Annex IX Parts A and B of the most recently revised Renewable Energy Directive (RED III), recycled carbon fuels, and synthetic aviation fuel derived from non-biomass material such as low-carbon hydrogen and renewable electricity.

ReFuelEU was designed to prevent SAF from putting pressure on global food and feed markets. Current eligibility guidelines, however, do not mitigate this risk entirely. For example, certain biofuel feedstocks, such as Category 3 animal fats, are not defined as "food and feed crops" in RED III but are also not listed in Annex IX. These materials can count toward ReFuelEU blending targets, although the regulation caps fuel derived from these feedstocks at 3% by volume. Incorporating them into SAF conflicts with their current uses in food and feed markets, as a 2022 ICCT briefing explained.[2]

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[1] Jane O'Malley, Nikita Pavlenko, and Stephanie Searle, *Estimating Sustainable Aviation Fuel Feedstock Availability to Meet Growing European Union Demand* (International Council on Clean Transportation, 2021), https://theicct.org/publication/estimating-sustainable-aviation-fuel-feedstock-availability-to-meet-growing-european-union-demand/.

[2] Chelsea Baldino and Jayant Mukhopadhaya, *Considerations for the ReFuelEU Aviation Trilogue* (International Council on Clean Transportation, 2022), https://theicct.org/publication/refueleu-definitions-trilogue-sep22/.

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We define "lowest risk" biomass to include "advanced biofuels" derived from domestically sourced and sustainably harvested lignocellulosic materials listed in Annex IX Part A of the RED III and domestically collected waste oils listed in Annex IX Part B. Lignocellulosic biomass can be converted to SAF via gasification followed by Fischer-Tropsch synthesis, pyrolysis, or alcohol-to-jet upgrading. Waste oil feedstocks can be upgraded to SAF using conventional hydroprocessing technologies.

Our updated analysis includes: 1) a bottom-up assessment of domestic and imported waste oil availability; 2) an updated assessment of lignocellulosic materials in the EU—building on 2021 research by Carraro, Searle, and Baldino—with a new sensitivity analysis of forestry residues and municipal solid waste availability; and 3) supplemental data from the literature.[3] We also update our yield assumptions for distillate fuel produced through the hydrotreated esters and fatty acids (HEFA) pathway, based on recent techno-economic assessments.

The Annex IX feedstock list was broadened in 2024 to include feedstocks such as intermediate crops and damaged crops, but we do not include those in this analysis.[4] We review and summarize our results below. Future work could estimate biomass availability in individual Member States.

AVAILABILITY OF WASTE FATS AND OILS

USED COOKING OIL

Waste fats and oils that are eligible under the ReFuelEU regulation include used cooking oil and inedible animal fats, because they fall under Annex IX, Part B of the RED III. The final regulation states that these feedstocks "are essential, as currently the most commercially mature technology to decarbonize air transport in the short term."[5] Thus, there is no cap on using waste fats and oils in the adopted version of ReFuelEU. That contrasts with the use of these feedstocks for other transportation modes. When the Renewable Energy Directive was amended in 2023, becoming RED III, a cap was maintained on using waste fats and oils to meet the overall target for transportation calculated on an energy or greenhouse gas (GHG) emissions intensity basis. Nevertheless, barring any newly added feedstocks, nearly all Annex IX Part B feedstocks produced in the EU are used to make biodiesel and renewable diesel today. The 2023 EU Biofuels Annual report published by the U.S. Department of Agriculture's Foreign Agricultural Service (USDA-FAS) indicates that 5.15 million tonnes (Mt) of these feedstocks were consumed in biodiesel and renewable diesel applications in 2021.[6] This volume includes 4.0 Mt of used cooking oil (UCO) and 1.15 Mt of Category 1 and Category 2 animal fats.

Although we cite UCO consumption data reported by USDA-FAS in previous studies, there appears to be reporting inconsistencies at the Member State level.[7] In correspondence with ICCT researchers, authors of the Biofuels Annual report noted

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[3] Camilla Carraro, Stephanie Searle, and Chelsea Baldino, *Waste and Residue Availability for Advanced Biofuel Production in the European Union and the United Kingdom* (International Council on Clean Transportation, 2021), https://theicct.org/publication/waste-and-residue-availability-for-advanced-biofuel-production-in-the-european-union-and-the-united-kingdom/.

[4] Commission Delegated Directive (EU) 2024/1405 of 14 March 2024 amending Annex IX to Directive (EU) 2018/2001 of the European Parliament and of the Council as regards adding feedstock for the production of biofuels and biogas, OJ L 17.5.2024, http://data.europa.eu/eli/dir_del/2024/1405/oj.

[5] Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation) (Text with EEA relevance), OJ L 31.10.2023, http://data.europa.eu/eli/reg/2023/2405/oj.

[6] Bob Flach, Sabine Lieberz, and Sophie Bolla, *European Union Biofuels Annual 2023* (U.S. Department of Agriculture Foreign Agricultural Service, 2023), https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels%20Annual_The%20Hague_European%20Union_E42023-0033.pdf.

[7] O'Malley, Pavlenko, and Searle, *Estimating Sustainable Aviation Fuel Feedstock*.

that UCO data are collected across multiple European FAS offices and are based on national biofuel consumption data for some Member States. In other cases, numbers are estimated based on "oilseeds and vegetable oil production, consumption, and trade statistics." This may explain annual discrepancies in UCO consumption data across multiple reporting years. For example, the 2019 FAS report listed UCO consumption in biodiesel and renewable diesel applications as 2.75 Mt while the 2023 report listed UCO consumption as 3.38 Mt that same year.[8]

In our updated availability assessment, we cite an analysis by Stratas Advisors to determine maximum UCO collection potential in the EU-27.[9] This analysis finds there is approximately **1.5 Mt of domestic UCO** available, based on a bottom-up assessment of collection sources. This recent estimate aligns with other assessments from the literature that report between 1.7 and 2.0 Mt of UCO supply in the EU, including the United Kingdom.[10] A considerable volume of UCO is also imported to the EU and consumed in the biofuels sector. European UCO imports are primarily sourced from Asia.[11] There is evidence that some producers have labeled virgin vegetable oil as UCO to receive policy subsidies in the United States and evidence that this same practice is occurring in the EU.[12] UCO fraud is feasible because it is difficult to identify biofuel sourced from virgin vegetable and waste oils during chemical testing. Therefore, we do not consider imported UCO volumes to be "lowest risk" in our assessment.

As the integrity of imported UCO is difficult to verify, we set the sustainable supply of UCO at domestic EU collection rates. Despite fraud concerns, both domestically collected and imported UCO are eligible feedstocks under ReFuelEU. If we include current import levels based on EU trade data as an upper bound in our estimates, the total availability of UCO increases to **3.4 Mt.** [13] We assume that domestic and imported UCO volumes do not increase in later years given that import volumes have already begun to slow.[14]

OTHER FATS AND OILS IN ANNEX IX, B

To estimate the availability of inedible tallow (Category 1 and 2 animal fats), we source data on inedible tallow consumption from the European Fat Processors and Renderers Association (EFPRA). EFPRA publishes annual data on animal fat production, organized by material classification. This data is a close approximation of domestic animal fat production within EU borders, as EFPRA's membership includes state-level associations throughout the EU.[15] EFPRA data indicates that inedible tallow production in the EU has

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[8] Bob Flach, Sabine Lieberz, and Sophie Bolla, *EU Biofuels Annual 2019* (U.S. Department of Agriculture Foreign Agricultural Service, 2019), https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_The%20Hague_EU-28_7-15-2019.pdf.

[9] Stratas Advisors, *UCO Imports: Unfair Competition with EU UCO Industry?* (Transport & Environment, 2024), https://www.transportenvironment.org/uploads/files/TE_UCO-Study_Stratas_11062024_2024-06-17-103904_bjrt.pdf.

[10] Anouk van Grinsven et al., *Used Cooking Oil as Biofuel Feedstock in the EU* (CE Delft, 2020), https://cedelft.eu/wp-content/uploads/sites/2/2021/04/CE_Delft__200247_UCO_as_biofuel_feedstock_in_EU_FINAL-v5.pdf.

[11] "EU Biofuel Plan Increases Risk of Fraudulent Imports from Asia: Study," *Euractiv*, February 22, 2022, https://www.euractiv.com/section/biofuels/news/eu-biofuel-plan-increases-risk-of-fraudulent-imports-from-asia-study/.

[12] European Commission, European Anti-Fraud Office, *The OLAF Report 2019: Twentieth Report of the European Anti-Fraud Office, 1 January to 31 December 2019* (Publications Office of the European Union, 2020), https://data.europa.eu/doi/10.2784/8525.

[13] "Access2Markets," European Commission, accessed June 17, 2024, https://trade.ec.europa.eu/access-to-markets/en/home.

[14] Veronika Prykhodko, "China's UCO Exports to the US Boosted, While Flow to the EU Slows in 2020-2023," Fastmarkets, January 8, 2024, https://www.fastmarkets.com/insights/chinas-uco-exports-boost-to-us-slow-to-eu/.

[15] Chris Malins, *The Fat of the Land: The Impact of Biofuel Demand on the European Market for Rendered Animal Fats* (Cerulogy, May 2023), https://www.transportenvironment.org/wp-content/uploads/2023/05/Cerulogy_Fat-of-the-land_May_23.pdf.

leveled off over the past decade, a trend which we assume will remain constant in future years. Approximately **0.57 Mt of inedible tallow** was rendered by EPRA members in 2021, which we adopt as our domestic availability estimate. We cite EU trade data on animal fats as our upper bound, which increases total availability to **0.65 Mt**.[16]

Feedstocks not defined as "food and feed" in RED III, but which are also not listed in Annex IX, can count toward ReFuelEU blending targets. They are capped at 3% by volume. Potential non-Annex IX feedstocks that could be used for advanced biofuels production are assessed in a 2021 European Commission report.[17] Many of these feedstocks already have current uses in other industries.[18] Diverting these feedstocks to SAF production could generate indirect GHG emissions, because displacement from their current use would necessitate substitution by another material with its own emissions. In the case of oily and fatty feedstocks, the replacement material is often vegetable oil such as palm or soy. Category 3 animal fats, defined as fats that are fit for human and animal consumption, would fall into this category. They are already used in other sectors, such as food, feed, and soapmaking.

Category 3 animal fats are an attractive feedstock for SAF production, because they can be refined using HEFA, the only commercially mature SAF technology. The EU does not closely track the production of Category 3 animal fats, so we rely on industry data to estimate annual production rates. We supplement EFPRA data reported in 2021 with trade data reported by the European Commission for the same year to estimate the quantity of domestic Category 3 animal fat production and net imports, respectively. [19] In total, we estimate that the EU consumed **2.41 Mt** of this feedstock market-wide in 2021, most if it sourced domestically. The consumption of Category 3 animal fats has been steadily rising since EFPRA began collecting data in 2009. Process improvements to increase fat recovery during rendering may explain some of this growth, as well as market conditions that incentivize these fats to be rendered rather than incorporated directly into wet pet food.[20]

AVAILABILITY OF LIGNOCELLULOSIC MATERIALS

SAF made from lignocellulosic feedstocks is less commercially mature than SAF produced from waste oils. Lignocellulosic feedstocks are in far greater supply than waste oils but could lead to indirect emissions impacts if they are diverted from existing uses in non-transport applications.[21] We estimated the domestic supply of agricultural residues, forestry residues, and the biogenic portion of municipal and industrial waste in the EU in 2030. Consistent with Annex IX Part A, this does not include the portion of household waste subject to recycling targets under Directive 2008/98/EC. These materials make up the largest sources of available feedstock under Annex IX Part A but are not fully comprehensive. Annex IX of the consolidated text of Directive (EU) 2018/2001 includes the current list of eligible feedstocks, most recently updated in March 2024.[22]

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[16] European Commission, "Access2Markets."

[17] European Commission, Directorate-General for Energy, *Assessment of the Potential for New Feedstocks for the Production of Advanced Biofuels: Final Report* (Publications Office of the European Union, 2022), https://data.europa.eu/doi/10.2833/719121.

[18] Baldino and Mukhopadhaya, *Considerations for the ReFuelEU Aviation Trilogue*.

[19] Malins, *The Fat of the Land*; European Commission, "Access2Markets."

[20] Malins, *The Fat of the Land.*

[21] O'Malley, Pavlenko, and Searle, *Estimating Sustainable Aviation Fuel Feedstock.*

[22] Consolidated text: Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance), July 16, 2024, http://data.europa.eu/eli/dir/2018/2001/2024-07-16.

AGRICULTURE AND FORESTRY RESIDUES

The 2021 study by Carraro, Searle, and Baldino provides the most recent estimate of lignocellulosic feedstock availability in the EU, building on previous ICCT studies.[23] This includes agricultural residues from barely, maize, oat, olives, rapeseed, rice (paddy), rye, soybeans, sunflower, triticale, and wheat. The authors estimate crop residue production based on crop production data from the Food and Agriculture Organization of the United Nations (FAO) and average 2015–2019 yield estimates.[24] Crop production and yield projections for 2023 are drawn from European Commission estimates and interpolated for interim years.[25] In total, we estimate that **83.3 Mt** of agricultural residues could be processed into SAF in 2030.

Carraro, Searle, and Baldino also estimate the production of forestry residues based on total roundwood harvest data from FAO. This data is adjusted to account for the portion of residues that should remain in situ to maintain soil quality. As noted in Searle and Malins, the original study that Carraro, Searle, and Baldino's methodology is based on, forestry residues include the unused portions of felled trees, including tops and limbs, but exclude the below-ground parts of stumps.[26] Any roundwood that is eligible under Annex IX, A is not included in ICCT's assessment of available forestry residues. This is due to its long carbon payback period, or the time it takes for biogenic CO_2 to be sequestered from plant regrowth.

A previous ICCT blog explains why using roundwood for bioenergy does not have a positive climate impact.[27] In short, the life-cycle accounting convention for biofuels in the EU assumes that because biogenic CO_2 is sequestered by replacement biomass over short timescales, bioenergy combustion has a net-zero CO_2 impact.[28] In reality, CO_2 emissions from biomass are time-dependent and could lead to warming impacts before the completion of a cropping rotation period.[29] Rotation periods for European forests can be more than 100 years, which corresponds to the length of time it takes for biomass to fully sequester carbon from the atmosphere.[30] We match an assumed rotation period of 100 years with the associated biogenic global warming potential (GWP_{bio}) from Cherubini et al. and find that combusted roundwood releases emissions that are equivalent to 43% of fossil CO_2 on a 100-year timescale.[31] On a 20-year timescale, Cherubini et al. find that combusted roundwood releases emissions that are up to 96% of fossil CO_2.

Biomass availability for this feedstock category is expected to remain constant through 2050 at an estimated **11.2 Mt**. While the forestry residues included in this

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[23] Carraro, Searle, and Baldino, *Waste and Residue Availability*.

[24] FAOSTAT: Crops and Livestock Products," Food and Agricultural Organization of the United Nations, accessed June 17, 2024, https://www.fao.org/faostat/en/#data/QCL.

[25] European Commission, Directorate-General for Agriculture and Rural Development, *EU Agricultural Outlook for Markets, Income and Environment 2020-2030* (Publications Office of the European Union, 2020), https://data.europa.eu/doi/10.2762/252413.

[26] Stephanie Y. Searle and Christopher J. Malins, "Waste and Residue Availability for Advanced Biofuel Production in EU Member States," *Biomass and Bioenergy* 89 (June 2016): 2–10, https://doi.org/10.1016/j.biombioe.2016.01.008.

[27] Camilla Carraro and Chelsea Baldino, "Felling for Power is Failing the Climate: Why Burning Trees for Energy Makes No Sense," *International Council on Clean Transportation* (blog), July 5, 2021, https://theicct.org/felling-for-power-is-failing-the-climate-why-burning-trees-for-energy-makes-no-sense/.

[28] Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2021—The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st ed. (Cambridge University Press, 2023), https://doi.org/10.1017/9781009157896.

[29] Alissa Kendall, Brenda Chang, and Benjamin Sharpe, "Accounting for Time-Dependent Effects in Biofuel Life Cycle Greenhouse Gas Emissions Calculations," *Environmental Science & Technology* 43, no. 18 (2009): 7142–7147, https://doi.org/10.1021/es900529u.

[30] Soňa Zimová et al., "Reducing Rotation Age to Address Increasing Disturbances in Central Europe: Potential and Limitations," *Forest Ecology and Management* 475 (2020): 118408, https://doi.org/10.1016/j.foreco.2020.118408.

[31] Francesco Cherubini et al., "CO_2 Emissions from Biomass Combustion for Bioenergy: Atmospheric Decay and Contribution to Global Warming," *GCB Bioenergy* 3, no. 5 (October 2011): 413–26, https://doi.org/10.1111/j.1757-1707.2011.01102.x.

assessment are a by-product of roundwood production and do not have other uses, nongovernmental organizations have called on the European Commission to remove industrial roundwood from the RED eligibility list.[32] We estimate the potential impact of this restriction on woody biomass availability by adjusting the supply of roundwood downward by the share of total roundwood currently burned as fuel in each Member State. We adjust this share by a factor of 0.63 to account for the price elasticity supply of roundwood; that is, we expect the current share of roundwood consumed in the power sector to decrease by 63% and the remaining to be consumed in new markets.[33] We apply the same residue conversion factors and competing uses as above to determine availability. This reduces the overall availability of roundwood in the EU by 52% and the availability of all forestry residues by 25% to **8.4 Mt**.

MUNICIPAL SOLID WASTE

The biogenic portion of municipal solid waste (MSW)—including paper and cardboard, wood waste, animal and mixed food waste, household and similar wastes, and common sludges—is the final category estimated in this analysis. In total, MSW availability equates to **66.8 Mt** of dry organic matter in 2030. MSW availability increased substantially from our previous study due to the updated assumption that waste incinerated for energy recovery could be diverted to SAF instead, due to the low efficiency of burning these wastes as fuel on site.[34] Carraro, Searle, and Baldino also assume that recycled MSW, which is unavailable for SAF production, will not exceed the recycling targets for 2030 and 2050 from the Waste Framework Directive, i.e., 60% recycling of total MSW produced in 2030 and 80% in 2050.[35]

The consultant group Equanimator has compiled data on the average efficiency of waste incineration in Europe and found that it ranges from 14% to 26% for MSW converted to electricity. The energy efficiency of SAF conversion for MSW feedstocks is roughly 20%, assuming a 50% energy yield for gasification via Fischer-Tropsch (FT-gasification) and a 40% overall efficiency of aircraft engines.[36] Given that waste incineration can be a more efficient use of MSW disposal than fuel conversion, we subtract the portion of MSW diverted to waste incineration from our availability totals in a sensitivity analysis. This reduces 2030 MSW feedstock availability to **29.2 Mt**.

AVAILABILITY OF OTHER FEEDSTOCKS

Annex IX Part A includes additional feedstocks that may be converted to SAF under the adopted ReFuelEU regulation. Many are used in niche applications today, but we consider feedstocks that are energy dense and composed of fatty compounds as likely candidates for SAF production because they can be refined through HEFA technology. These include tall oil pitch (an intermediate grade of crude tall oil, a byproduct of the paper and pulping industry), crude glycerine, and palm oil mill effluent (POME). Additional feedstocks could be eligible under the 3% volume cap but we exclude those from this analysis given that they all carry sustainability risk.

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[32] Forest Defenders Alliance, "EU Policymakers Agree on New Restrictions on Forest Biomass in the Renewable Energy Directive," *Forest Defenders Alliance* (blog), March 30, 2023, https://forestdefenders.eu/eu-policymakers-agree-on-new-restrictions-on-forest-biomass-in-the-renewable-energy-directive/.

[33] Gert-Jan Nabuurs and M.J. Schelhaas, "Future Wood Supply from European Forests; Implications for the Pulp and Paper Industry," 2003.

[34] Equanimator, *Debunking Efficient Recovery: The Performance of EU Incineration Facilities* (Zero Waste Europe, 2023), https://zerowasteeurope.eu/wp-content/uploads/2023/01/Debunking-Efficient-Recovery-Full-Report-EN.docx.pdf.

[35] "Waste Framework Directive," European Commission, accessed June 17, 2024, https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en.

[36] Uisung Lee et al., "Life Cycle Analysis of Gasification and Fischer-Tropsch Conversion of Municipal Solid Waste for Transportation Fuel Production," *Journal of Cleaner Production* 382 (2023): 135114, https://doi.org/10.1016/j.jclepro.2022.135114; National Academies of Sciences, Engineering, and Medicine, "Chapter 3: Aircraft Gas Turbine Engines," in Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions (The National Academies Press, 2016), https://doi.org/10.17226/23490.

We obtained data on the supply of crude tall oil (CTO) from a 2021 study by Aryan and Kraft.[37] CTO production is expected to steadily grow through 2030 due to softwood kraft pulping (SKP) capacity expansions. We extrapolate European CTO production rates through 2035, assuming the annual growth rate of 1.5% projected by Aryan and Kraft. In total, we estimate that the EU has a potential CTO supply of 0.75 Mt in 2030. However, the pine chemicals industry has few feasible substitutes for CTO to use in making adhesives and other products.[38] Therefore, we only consider CTO diversion from energy recovery to be financially viable. We note that diverting CTO from energy recovery—that is, from being consumed as fuel at the pulp mills—to the transport sector would result in the need for a substitute energy source at the mills. The likely replacement material would be natural gas or heavy fuel oil, which both have significant GHG emission intensities.[39]

Tall oil heads and pitch consumed for energy recovery make up approximately 32% of total CTO production.[40] This equates to **0.24 Mt** of feedstock that could be converted to SAF production in 2030.

We also investigate the availability of crude glycerine, a byproduct of biodiesel refining that is included on the Annex IX Part A list. Glycerine is produced at approximately 10% the rate of biodiesel; thus, we consider projections for biodiesel EU production in 2030 to estimate glycerine availability. The most recent EU agricultural outlook report predicts that biodiesel demand will peak in 2023 and decline by 24% through 2031 due to vehicle electrification and phaseout policies for palm oil and other high-risk feedstocks.[41] We adopt the report's assumption of 13.1 billion liters for EU biofuel demand in 2030 which corresponds to 1.31 billion liters, or 1.15 Mt, of crude glycerine production.

Once crude glycerine is refined to remove impurities, it is consumed in various applications across the chemicals, pharmaceuticals, and food and beverage industries.[42] It is unlikely that refined glycerine (i.e., glycerol) would be diverted toward the biofuel sector because of its high economic value; it is more likely that crude glycerine would be diverted from its existing uses in animal feed, energy recovery, and cement manufacturing. We adjust our availability estimates for crude glycerine by half to account for the share of refined glycerine used in more niche product industries, thus making our estimate of crude glycerine available for SAF production **0.58 Mt**.[43] Diverting the remainder toward biofuel production would result in some indirect emission impacts from the substitution of other materials for existing glycerine applications.

Palm oil mill effluent (POME) is the final Annex IX feedstock we consider in our analysis. POME is waste produced at palm oil mills, primarily located in Indonesia and Malaysia. It contains an oil called palm oil sludge, which can be converted to SAF via the HEFA

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[37] Venkat Aryan and Axel Kraft, "The Crude Tall Oil Value Chain: Global Availability and the Influence of Regional Energy Policies," *Journal of Cleaner Production* 280 (2021): 124616, https://doi.org/10.1016/j.jclepro.2020.124616.

[38] Jane O'Malley, Stephanie Searle, and Nikita Pavlenko, *Indirect Emissions from Waste and Residue Feedstocks: 10 Case Studies from the United States* (International Council on Clean Transportation, 2021), https://theicct.org/publication/indirect-emissions-from-waste-and-residue-feedstocks-10-case-studies-from-the-united-states/.

[39] Chris Malins, *Waste Not Want Not: Understanding the Greenhouse Gas Implications of Diverting Waste and Residual Materials to Biofuel Production* (International Council on Clean Transportation, 2017), https://theicct.org/publication/waste-not-want-not-understanding-the-greenhouse-gas-implications-of-diverting-waste-and-residual-materials-to-biofuel-production/.

[40] Sarah A. Cashman, Kevin M. Moran, and Anthony G. Gaglione, "Greenhouse Gas and Energy Life Cycle Assessment of Pine Chemicals Derived from Crude Tall Oil and Their Substitutes," *Journal of Industrial Ecology* 20, no. 5 (2016): 1108–21, https://doi.org/10.1111/jiec.12370.

[41] European Commission, Directorate-General for Agriculture and Rural Development, *EU Agricultural Outlook for Markets, Income and Environment 2021-2031* (Publications Office of the European Union, 2021), https://data.europa.eu/doi/10.2762/753688.

[42] Malins, *Waste Not Want Not.*

[43] Rosaria Ciriminna et al., "Understanding the Glycerol Market," *European Journal of Lipid Science and Technology* 116, no. 10 (2014): 1432–39, https://doi.org/10.1002/ejlt.201400229.

process. Baldino et al. report a global potential for up to **1.0 Mt** of palm oil sludge to be available for biofuel production, after accounting for oil extraction rates from wastewater streams.[44] We note that data on POME production is scarce and may be subject to reporting fraud, since POME is one of few feedstocks on the Annex IX Part A list that can be converted to biofuel using first-generation conversion technologies.[45] For this reason, Germany has already excluded POME from receiving double counting towards its national implementation of the RED II, the THG Quote, unlike other Annex IX, A biofuels.[46]

Ethanol produced from industrial flue gas emitted during steelmaking also qualifies toward the overall SAF targets as "recycled carbon aviation fuel." In 2022, the EU produced 136 million tonnes of steel, and a corresponding 34 Mt of flue gas consisting of carbon monoxide and hydrogen.[47] We assume that 80% of this volume is used for onsite energy recovery and the remainder is typically flared.[48] The EU restricts the share of flue gas used for onsite energy recovery from qualifying as SAF due to the displacement impact of diverting the flue gas to the transport sector.[49] Thus, we only consider the approximately 6.74 Mt of flue gas that is flared as an available fuel source. Assuming a conversion factor of 3.65 tonnes of flue gas per tonne of ethanol, we find that there is approximately **1.84 Mt** of flue gas ethanol potential in the EU.

STUDY COMPARISON

Our feedstock estimates for all pathways increased in this assessment relative to our 2021 study (Table 1). Some of the largest changes can be traced to changes in UCO and animal fats reporting. Further, our results shifted because of increases in the estimated availability of lignocellulosic feedstocks resulting from reduced competition for these materials in other sectors such as heat and power. This change was most notable for MSW due to the updated assumption that waste incinerated for energy recovery can be diverted to SAF.

In this update, we assess the availability of three new feedstocks including Category 3 animal fats, crude glycerine, and POME. Using these feedstocks for SAF would likely trigger indirect emission impacts, but they would still qualify under ReFuelEU blending mandates. Unlike in our 2021 study, we do not assess the availability of cover crops (also known as intermediate crops). Cover crops qualify under ReFuelEU blending targets under the broadened Annex IX list but warrant additional analysis to quantify their contribution.

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[44] Chelsea Baldino, Stephanie Searle, and Yuanrong Zhou, *Alternative Uses and Substitutes for Wastes, Residues, and Byproducts Used in Fuel Production in the United States* (International Council on Clean Transportation, 2020), https://theicct.org/publication/alternative-uses-and-substitutes-for-wastes-residues-and-byproducts-used-in-fuel-production-in-the-united-states/.

[45] "EU-Backed Green Auditor Cracks down on China Island Biofuel Trade," *Euractiv*, June 23, 2023, https://www.euractiv.com/section/fuels/news/eu-backed-green-auditor-cracks-down-on-china-island-biofuel-trade/.

[46] Peter Kasten and Julius Jöhrens, *Die Einbindung der Elektromobilität in die THG-Quote* [The integration of electromobility into the GHG quota] (Öko-Institu e.V., 2022), https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Verkehr/thg_quote_anrechnung_bf.pdf.

[47] World Steel Association, *2023 World Steel in Figures*, 2023, https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2023-4.pdf.

[48] Jason Collis et al., "Deriving Economic Potential and GHG Emissions of Steel Mill Gas for Chemical Industry," *Frontiers in Energy Research* 9 (2021), https://doi.org/10.3389/fenrg.2021.642162.

[49] Commission Delegated Regulation (EU) 2023/1185 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a minimum threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels, OJ L 157, 20.6.2023, http://data.europa.eu/eli/reg_del/2023/1185/oj.

Table 1

Comparison of feedstock availability estimates in 2030 (million tonnes)

Conversion pathway	Availability (2021 estimate)	Availability (2024 estimate)
Inedible tallow	0.8	0.6
Category 3 animal fats	—	2.4
Used cooking oil	1.6	3.4
Municipal solid waste	21.2	29.2–66.8
Agricultural residues	76.5	83.3
Forestry residues	5.1	8.4–11.2
Cover crops	7.2	—
Industrial flue gas ethanol	2.2	1.8
Crude tall oil (heads and pitch)	—	0.2
Crude glycerine	—	0.6
Palm oil mill effluent	—	1.0
Total	**114.5**	**131.2–171.5**

ESTIMATED SAF PRODUCTION IN 2035

We combine the above feedstock availability estimates to calculate the quantity of SAF that could be produced in the EU in 2035. That year is expected to be an important inflection point for the industry when ReFuelEU blending targets ramp up to 20%, with a 5% power-to-liquids subtarget. This leaves 15% of the SAF target to possibly be met with bio-SAF. Our bio-SAF production estimates account for process conversion yields and for the share of SAF produced as part of an aviation-optimized refinery product slate. We summarize our yield conversion estimates below.

Yield estimates for HEFA are drawn from techno-economic assessments compiled by researchers at Washington State University and assume a conversion yield of 0.83 kg of fuel per kilogram of oil feedstock.[50] These estimates are adjusted by a factor of 0.59 to account for the share of SAF produced at refineries under a jet-optimized process configuration.[51] Yields vary for biomass gasification pathways and are based on values from the literature. In general, this pathway has a lower conversion yield between 0.11 and 0.22 kg of distillate fuel per kilogram of feedstock. Cellulosic materials such as biogenic MSW have low heating values, so they have low overall yields relative to other pathways on an energy basis. We assume that the FT gasification process has a conversion efficiency of 50% while the lower heating value (LHV) of cellulosic biomass ranges between 10 MJ/kg for MSW and 19 MJ/kg for forestry residues.[52] FT gasification output is then adjusted by a factor of 0.5 to account for the maximum share of jet fuel produced from hydrocarbon synthesis. Although the share of SAF produced at bio-refineries may be optimized in the future, facility-level data is currently limited. SAF supplier SkyNRG assumes that jet and diesel are produced in equal volumes at HEFA refineries today while SAF accounts for 35% of FT gasification output before 2030 and 50% of output after that point.[53] More

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[50] Kristin Brandt et al., Hydroprocessed Esters and Fatty Acids Techno-Economic Analysis v2.2, computer software (Washington State University, 2021), https://doi.org/10.7273/000001460.

[51] O'Malley, Pavlenko, and Searle, *Estimating Sustainable Aviation Fuel Feedstock.*

[52] Uisung Lee et al., "Life Cycle Analysis"; IEA Bioenergy, *Municipal Solid Waste and Its Role in Sustainability*, 2003, https://www.ieabioenergy.com/wp-content/uploads/2013/10/40_IEAPositionPaperMSW.pdf; Nike Krajnc, *Wood Fuels Handbook* (Food and Agriculture Organization of the United Nations, 2015).

[53] SkyNRG, *SAF Market Outlook: SkyNRG's Perspective on the ReFuelEU Aviation Initiative Proposal*, 2021, https://nordicelectrofuel.no/wp-content/uploads/2021/08/SkyNRG-Market-Outlook-on-SAF-Background-Analysis-JUL-2021.pdf.

optimistically, the World Economic Forum predicts that SAF output at HEFA plants could be as high as 70% after 2030.[54]

Glycerine can be combined with methanol to form isobutanol and upgraded into jet fuel via the alcohol-to-jet (ATJ) conversion process. In a 2014 study, Bauer and Hulteberg analyzed this process in a modeling study and found that glycerine could yield up to 0.75 tonnes of isobutanol per tonne of crude feedstock across a series of reaction steps.[55] We also consider the yield factor for isobutanol-to-jet upgrading reported by Geleynse et al. to calculate the maximum volume of SAF produced from the ATJ pathway.[56] As an alternative to this multistep conversion process, researchers have proposed that glycerine can be gasified to form syngas and converted to jet fuel via Fischer-Tropsch synthesis.[57] Both of these technology pathways remain in the research stage.

In total, we estimate that available feedstocks could yield a maximum of 17.3 Mt (22.6 billion liters) of SAF in 2035. This is equivalent to 31% of projected EU-27 jet fuel demand, assuming EU passenger and global freight growth rates from the ICCT's Vision 2050 report.[58] This quantity includes contributions from feedstocks that we deem to be "moderate" or "high" risk as discussed in the section below. If we limit our 2035 SAF availability projections to include only feedstocks presenting the "lowest" risk to sustainability, this drops to 26% of EU-27 jet fuel demand. We present a summary of feedstock availability, yield factors, SAF production, and the relative contribution toward 2035 jet fuel demand for each feedstock pathway in Table 2.

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[54] World Economic Forum, Clean Skies for Tomorrow, *Guidelines for a Sustainable Aviation Fuel Blending Mandate in Europe*, 2021, https://www3.weforum.org/docs/WEF_CST_EU_Policy_2021.pdf.

[55] Fredric Bauer and Christian Hulteberg, "Isobutanol from Glycerine – A Techno-Economic Evaluation of a New Biofuel Production Process," *Applied Energy* 122 (June 2014): 261–68. https://doi.org/10.1016/j.apenergy.2014.02.037.

[56] Scott Geleynse et al., "The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation," *ChemSusChem* 11, no. 21 (November 2018): 3728–41. https://doi.org/10.1002/cssc.201801690.

[57] Ruth Barbosa, "Reusing to Optimise: The Use of Glycerine in the Production of Sustainable Aviation Fuels," International PtX Hub, May 21, 2021, https://ptx-hub.org/reusing-to-optimise-the-use-of-glycerine-in-the-production-of-sustainable-aviation-fuels/.

[58] Brandon Graver et al., *Vision 2050: Aligning Aviation with the Paris Agreement* (International Council on Clean Transportation, 2022), https://theicct.org/publication/global-aviation-vision-2050-align-aviation-paris-jun22/.

Table 2

Estimated EU feedstock fuel yields and SAF production in 2035

Feedstock	Conversion pathway	Yield (kg fuel/kg feedstock)	Source	SAF production (Mt)	% 2035 jet fuel demand
Materials listed in Annex IX					
Inedible tallow (domestic)	HEFA	0.83	Brandt et al., 2021[a]	0.28	0.5%
Inedible tallow (imported)	HEFA	0.83	Brandt et al., 2021	0.04	0.1%
Used cooking oil (domestic)	HEFA	0.83	Brandt et al., 2021	0.74	1.3%
Used cooking oil (imported)	HEFA	0.83	Brandt et al., 2021	0.95	1.7%
Tall oil pitch	HEFA	0.83	Brandt et al., 2021	0.11	0.2%
Palm oil sludge	HEFA	0.83	Brandt et al., 2021	0.49	0.9%
Municipal solid waste	FT gasification	0.11	Lee et al., 2023[b]; IEA Bioenergy, 2003[c]	1.44–3.36	2.6–6.0%
Agricultural residues	FT gasification	0.19	Lee et al., 2023; Tumuluru, 2015[d]	8.18	14.6%
Forestry residues	FT gasification	0.22	Lee et al., 2023; Krajnc, 2015[e]	0.91–1.21	1.6–2.2%
Crude glycerine	Alcohol-to-jet	0.50	Bauer and Hulteberg, 2014[f]; Geleynse et al., 2018[g]	0.22	0.4%
Materials listed in Annex IX					
Animal fats (Category 3)	HEFA	0.83	Brandt et al., 2021	1.18	2.1%
Crude tall oil heads	HEFA	0.83	Brandt et al., 2021	0.02	0.03%
Industrial flue gas	Alcohol-to-jet	0.40	Handler et al., 2016[h]	0.55	1.0%

[a] Kristin Brandt et al., Hydroprocessed Esters and Fatt Acids Techno-Economic Analysis v2.2, computer software (Washington State University, 2021), https://doi.org/10.7273/000001460.

[b] Uisung Lee et al., "Life Cycle Analysis of Gasification and Fischer-Tropsch Conversion of Municipal Solid Waste for Transportation Fuel Production," *Journal of Cleaner Production* 382 (2023): 135114, https://doi. org/10.1016/j.jclepro.2022.135114.

[c] IEA Bioenergy, *Municipal Solid Waste and Its Role in Sustainability*, 2003, https://www.ieabioenergy.com/wp-content/uploads/2013/10/40_IEAPositionPaperMSW.pdf.

[d] Jaya Shankar Tumuluru, "Comparison of Chemical Composition and Energy Property of Torrefied Switchgrass and Corn Stover," *Frontiers in Energy Research* 3 (November 2015), https://doi.org/10.3389/fenrg.2015.00046.

[e] Nike Krajnc, *Wood Fuels Handbook* (Food and Agriculture Organization of the United Nations, 2015).

[f] Fredric Bauer and Christian Hulteberg, "Isobutanol from Glycerine – A Techno-Economic Evaluation of a New Biofuel Production Process," *Applied Energy* 122 (June 2014): 261–68. https://doi.org/10.1016/j.apenergy.2014.02.037.

[g] Scott Geleynse et al., "The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation," *ChemSusChem* 11, no. 21 (November 2018): 3728–41. https://doi.org/10.1002/cssc.201801690.

[h] Robert M. Handler et al., "Life Cycle Assessments of Ethanol Production via Gas Fermentation: Anticipated Greenhouse Gas Emissions for Cellulosic and Waste Gas Feedstocks," *Industrial & Engineering Chemistry Research* 55, no. 12 (March 2016): 3253–61, https://doi.org/10.1021/acs.iecr.5b03215.

We next organize our feedstocks by GHG emission risk to determine the share of ReFuelEU targets that could be solely met with the lowest-GHG feedstocks. Feedstocks are organized according to their indirect emission effects and likelihood of fraudulent reporting. Feedstocks that have indirect emissions impacts that may exceed the carbon intensity of fossil diesel are classified as "high risk." Feedstocks with limited availability and evidence of reporting fraud are labeled "moderate risk." Feedstocks with no competing uses, which are domestically sourced and sustainably harvested, are labeled "lowest risk."

Table 3
GHG classifications of eligible SAF feedstocks

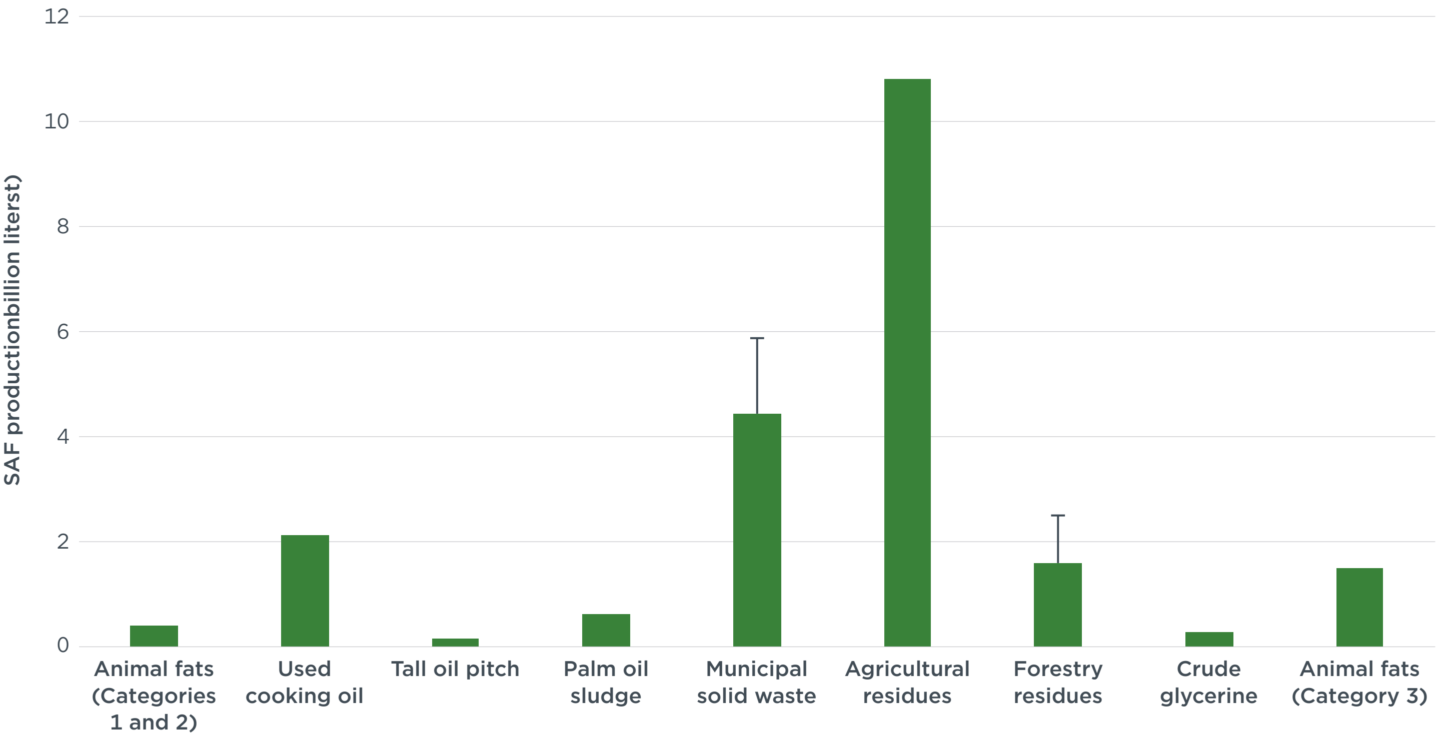
Feedstock	Classification
Materials listed in Annex IX	
Inedible tallow	Moderate risk
Used cooking oil (domestic)	Lowest risk
Used cooking oil (imported)	Moderate risk
Tall oil pitch	High risk
Palm oil sludge	Moderate risk
Municipal solid waste	Lowest risk
Agricultural residues	Lowest risk
Forestry residues, excluding roundwood	Lowest risk
Crude glycerine	Moderate risk
Materials not listed in Annex IX	
Category 3 animal fats	High risk
Industrial flue gas	Lowest risk
Crude tall oil heads	High risk

We find that the availability of "lowest risk" feedstocks could yield 25.6% of the 2035 demand for SAF in the EU-27. Thus, with a 5% synthetic aviation fuel target, there would be enough low-GHG advanced bio-SAF and recycled carbon aviation fuel available to meet the remaining 15% target in Europe, though the exact contribution would depend on how many conversion facilities could be constructed by that time. We estimate that the "high" and "moderate risk" feedstocks, including Category 3 animal fats and intermediate grades of crude tall oil intermediate, could provide an additional 3.0 Mt, or 5.4% of 2035 jet fuel demand. When considering additional feedstocks that may be added to Annex IX—such as non-food intermediate crops that we did not assess in this study—the potential would be even higher.

Lignocellulosic feedstocks make up the largest share of SAF potential followed by waste oils, including UCO and Category 3 animal fats. The total potential of SAF from feedstocks subject to the 3% volume cap is 1.2 Mt. Given there are feedstocks not on the Annex IX list in addition to Category 3 animal fats that could be used to produce SAF, it is likely the remainder of the 3% target could be met. We present our estimates for maximum EU SAF production by feedstock type in Figure 1.

Figure 1

Maximum SAF production from eligible ReFuelEU feedstocks in 2035



Note: Error bars show the potential production if municipal solid waste destined for incineration is diverted to SAF instead, and if industrial roundwood remains eligible under EU energy targets.

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The EU has enough raw material to produce between 15.9 and 18.8 billion liters of lowest-risk SAF in 2035. Nevertheless, lags associated with technology development and facility deployment will likely limit SAF production from lignocellulosic feedstocks in the coming decade. We revisit a facility deployment model from our 2021 assessment report, which assumes that each Member State deploys a maximum of one FT gasification facility before 2030 and an additional facility between 2030 and 2035. The size of these facilities would vary between 50 million gallons and 250 million gallons based on each country's quantity of available feedstock.[59] We estimate that 2035 SAF production could be reduced by 42%, or 6.7 billion liters, if deployment constraints limit SAF production from lignocellulosic pathways. Our maximum and constrained SAF production estimates by feedstock pathway are shown in Figure 2. Under both scenarios, we find that there is enough of the lowest-risk SAF supply to meet 2035 SAF blending targets.

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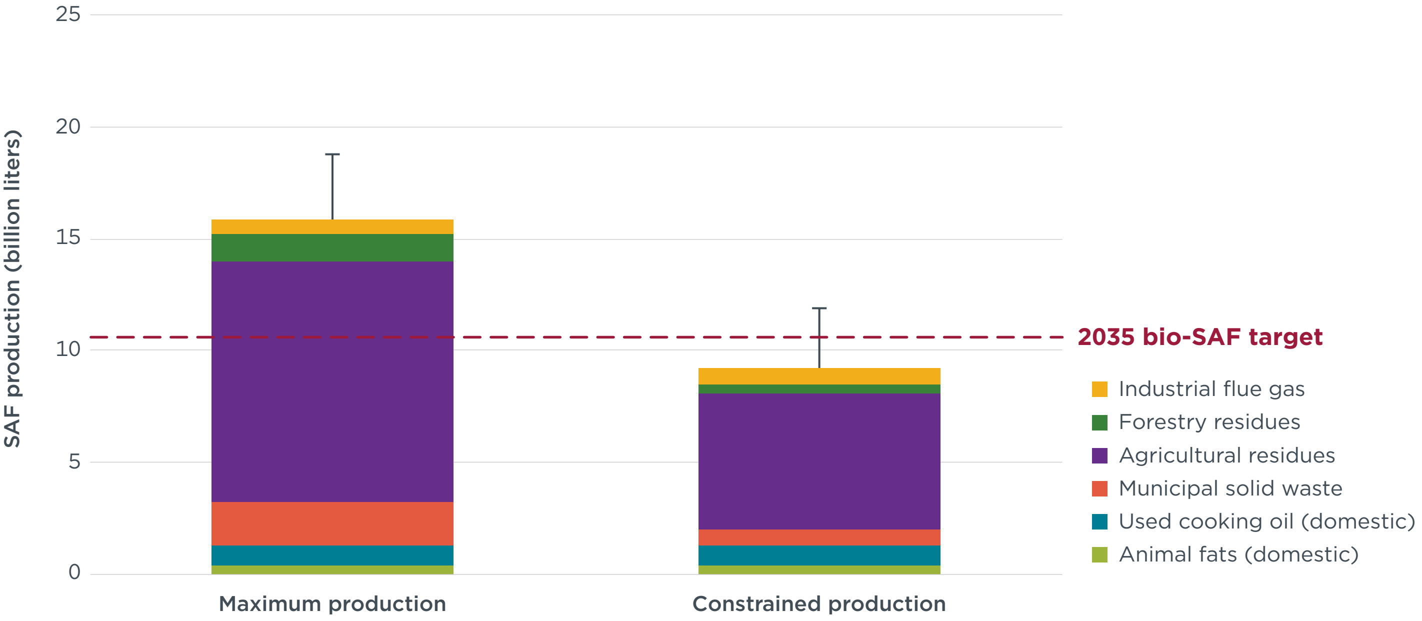
[59] Oscar P.R. van Vliet, André P.C. Faaij, and Wim C. Turkenburg, "Fischer–Tropsch Diesel Production in a Well-to-Wheel Perspective: A Carbon, Energy Flow and Cost Analysis," *Energy Conversion and Management* 50, no. 4 (2009): 855–876. https://doi.org/10.1016/j.enconman.2009.01.008.

Figure 2

Estimated 2035 SAF production from "lowest risk" feedstocks



Note: Constrained production assumes a maximum of one FT gasification plant deployed per EU Member State by 2030 and a second plant by 2035. Maximum production assumes no constraints on production output. Error bars show the potential production if municipal solid waste destined for incineration is diverted to SAF instead, and if industrial roundwood remains an eligible biofuel.

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In conclusion, we find that near- to midterm SAF blending targets can be achieved with available low-GHG biomass without the use of high-risk feedstocks. Meeting 2050 targets of up to 35% bio-SAF will prove more challenging. Given the abundance of low-GHG lignocellulosic feedstocks, it is critical to broaden investment beyond the near-term HEFA projects for processing waste fats and oils. Building facilities to produce biofuels from lignocellulosic materials would help ensure that the supply of SAF is sufficient to meet longer-term blending targets.

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